

Use of GPS Phase Measurements to Improve Vertical Refractivity Profiles in the Boundary Layer

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LONG TERM GOAL

The goal is to develop GPS remote sensing techniques to determine atmospheric refractivity profiles and to aid in the detection of oceanic boundary layers from a ship.

SCIENTIFIC OBJECTIVES

The primary scientific objective of this research is to develop GPS sounding techniques for ground based atmospheric profiling. Atmospheric profiling with GPS from space has been demonstrated (i.e. Ware et al. 1996, Rocken et al., 1997). Ground based GPS receivers have been used to determine integrated atmospheric water vapor above a site (i.e. Rocken et al., 1993), and along the ray paths to GPS satellites (Ware et al., 1997), but profiling techniques with ground-based GPS observations are still under development. Because of the large number of globally operating permanent GPS networks, ground-based profiling, if it proves feasible and accurate, will provide a large additional data set for atmospheric science and weather prediction applications. This data set will be especially useful for detailed monitoring of water vapor, one of the most important and yet least well defined atmospheric constituents.

APPROACH

We are pursuing a three-step approach to reach the long-term goal of refractivity profiling with GPS from a ship: (1) Develop and test GPS single slant measurement techniques, (2) Develop techniques to interpret these slant measurements, and (3) Develop a system for a mobile platform. We are presently working on (1) and (2). The porting of the technique to a mobile platform shall begin after the feasibility of the proposed technique has been demonstrated with GPS receivers from fixed sites.

WORK COMPLETED

The GPS phase from a single satellite can be measured with mm precision. Assuming that transmitter and receiver location are known and that the ionosphere can be removed with dual frequency data, this phase measurement is affected by atmospheric signal delay and bending, multipath, and receiver/transmitter clock errors. For this project the neutral atmospheric part is the signal, and clock errors and multipath errors have to be removed. Clock errors can be removed either by double differencing (DD) or by explicit estimation of receiver and transmitter clock behavior. We are investigating several approaches.

Double Difference to Zero Difference Techniques. DD works well but has the disadvantage that it also generates double differences of the tropospheric slant observations, which are complicated to interpret. Under the current grant UCAR has developed a technique to take GPS double difference residuals and, to extract the so-called zero difference residuals from these.

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We are presently testing the technique with simulated data and with real data from several GPS networks. For the data simulations we generate synthetic GPS observation, which are affected by simple, assumed direction dependent delays. We then process the data in a double difference mode and attempt to extract the single site direction dependent errors. Initial results are very encouraging and demonstrate that we can very accurately measure direction-dependent atmospheric delays with this technique.

An other approach to single slant observation is to form a double difference between two sites that are separated by a very long baseline (i.e. Boulder and Bermuda or east-coast sites). A satellite that is setting below the horizon to the East (West is blocked by the mountains) in Boulder is still well above the horizon as seen from an east coast site. Thus most of the phase change in the DD (assuming that the second satellite in the double difference is at reasonably high elevation angles relative to both sites) comes from the Boulder slant path. This slant observation is free of clock errors. It is however affected by orbit and geometry errors, which do not cancel for such a long baseline. Assuming orbit errors of 5 cm rms and position uncertainties at the 2-3 cm level these errors will be small compared to the total tropospheric delay signal at low elevation angles. More importantly, the rate of change of these errors will be much smaller than the rate of change due to the troposphere. Since the rate of change and the resulting bending angles shall be used for slant profiling, the technique may be the easiest approach to obtaining atmospheric profiles based on ground-based GPS observations.

Clearly, both double difference techniques described are not directly applicable to Navy's stand-alone shipboard system, but the techniques are still useful to test the concept of ground-based profiling and to validate the single receiver slant measurements described next.

Single Receiver Slant Measurements. A more common approach to obtaining zero-difference range measurements is direct clock estimation. The GPS transmitter clock offsets, due to Selective Availability (S/A) and clock instabilities, can be estimated with the global GPS network operated by the IGS. These clock solutions are computed and provided for example by the Jet Propulsion Laboratory (JPL). We can use these GPS clock corrections and data from ground receivers to determine the clock behavior of the ground receiver site. If the clock at the ground receiver site is of very high quality it may be sufficient to estimate the clock drifts as a low-order polynomial, or possibly not to estimate the clock drift at all.

We tested point positioning with JPL's GIPSY software and with the Bernese GPS software to evaluate slant path delay measurements with these two high accuracy software packages. This technique, once demonstrated with a fixed site, will be applicable on ships if (a) S/A is turned off or the user is authorized to measure non frequency-dithered carrier data, or (b) if clock corrections are broadcast in near-real-time by satellite globally as is planned by the FAA for the continental US now, and (c) if the shipboard GPS receiver location can be monitored very accurately with a combination of GPS and inertial navigation systems.

Clock Tests. Because of the importance of a high-quality clock at the ground receiver for this research, Dr. Kenn Anderson has purchased a highly stable Datum FTS clock. We tested the Datum clock with Turbo Rogue GPS receivers. We ran two receivers on a zero baseline at UCAR with two different clock inputs. One GPS receiver used a Rubidium oscillator as its clock source and the other used the Datum FTS clock. For comparison purposes, we obtained data from two IGS global tracking sites: USNO which uses a Hydrogen Maser that is steered to the U.S. Naval Observatory (USNO) Master clock [UTC(USNO)] and Bermuda which uses the Turbo Rogue internal oscillator internally steered to GPS time using pseudo-range clock solutions.

The data were analyzed using post-processed orbits and satellite clocks provided by JPL at 30-sec intervals. Using these data, we can estimate the receiver position and clock offset every 30 seconds using phase data in a point positioning mode (the GPS data is not differenced). These clock solutions are good to better than 1 nsec. The Datum FTS clock showed a large drift. We are not concerned about such a drift as it can easily be estimated. What is more concerning is a step-like clock behavior that is displayed after low-order drift terms have been removed.

Our tests indicate that the Datum clock that we purchased is not performing sufficiently well for high accuracy slant observations with GPS (0.1 nsec clock jumps correspond to 3 cm of delay and approximately 5 mm of water vapor along the receiver-to-transmitter line-of-sight). We are presently working with Datum to understand this clock behavior and to fix it.

High Gain Antenna Tests - San Diego Tests. Dr. Kenn Anderson collected a data set using a high-gain antenna and the accurate clock. The purpose of the high-gain antenna is to track satellite signals near the horizon without loss of lock. From previous data set it was clear that cycle slips due to loss of lock are frequent at low elevations. We processed the data and showed that the receiver tracked reliably down to minus 2 degrees. However, because of the clock behavior of the Datum clock we do not think that this data set (during which only very few satellites were tracked) can be used for profiling tests.

High Gain Antenna Tests - Boulder Tests. High gain antennas can help in tracking GPS signals near the horizon. But since these antennas do not observe all GPS satellites that are in view (i.e. antennas at high elevations and "behind" the high gain antenna are not tracked) their data are not sufficient for computing good position, and more importantly clock solutions for the ground receiver. This problem can be overcome in several ways: (a) Use a clock that is so good that the clock solution does not have to be computed, (b) Use a two antenna setup with one omni-directional antenna for sensing low-elevation slant observations and the other antenna for observing high-gain setting satellites, and (c) Same as the previous way but with a good clock that can be estimated as a low-order polynomial instead of on an epoch-by-epoch basis. We are testing the approach (c), allowing us to track all satellites in view to determine the clock behavior. The clock is set up as an external clock that is driving two receivers, but it could also be an internal clock in either receiver. We can then use the clock solution obtained with the data from receiver 1 to analyze the data from receiver 2. We have been operating two TurboRogue receivers in this mode for several weeks on the roof of our office at UCAR.

Development of Inversion Techniques. When observing GPS with a ground-based receiver at low elevation angles both phase and amplitude are subjected to considerable variations caused by refractive slowing of the signal in the atmosphere and by interference of the direct and reflected signals (multipath). For marine observations the amplitude interference pattern is caused mainly by the reflection from the sea surface. This pattern, which often has a rather regular structure, may be well deciphered, and used for the assessment of the vertical structure of refractivity in the boundary layer (Anderson, 1994). Since the problem is ill conditioned, the usage of any complementary data to increase the robustness is desirable.

We use the phase (Doppler) observational data for the reconstruction of a vertical refractivity profile. It is known that to solve this ill-conditioned problem some auxiliary information is required. Normally it results in searching for an approximate solution (instead of the exact one, which may be very far from the truth) inside some limited space. The two known methods are optimal estimation (also known as statistical regularization), and Tikhonov-Miller regularization. We are testing

optimal estimation. For this method some 1st guess of the solution is necessary. This 1st guess may be taken from other observations, or from the assessment based on the amplitude interference pattern (Anderson, 1994).

Our initial results look encouraging, and we now need to proceed with tests using real data. A key question which needs to be investigated is the impact of any horizontal inhomogeneity of refractivity and the resulting variations of the observational bending angles on the optimal estimation. The impact of horizontal inhomogeneity may be treated as random observational errors when solving the inverse problem in the assumption of the spherical symmetry, but its magnitude is yet to be determined. Tests with real observational data collected in Boulder are in progress now.

IMPACT/APPLICATIONS

Remote sensing of atmospheric features and refractivity profiles with GPS promises to impact Navy operations and provide a new data set for improved numerical weather prediction. Specifically, there are a variety of potential benefits to the Navy that will be provided by an enhanced GPS Sounder using phase and amplitude data to estimate improved refractivity profiles in the boundary layer. They include:

- Provides a passive, stand-alone, cost-effective method for shipboard and land-based boundary layer profiling and weather forecasting applications.
- Complements and strengthens ongoing SSC-SD GPS Sounder with no additional equipment required.
- Reduces reliance on high-cost, active radiosonde techniques, which often cannot be used during EMCON.
- Leverages ~\$15 B DOD investment in the GPS, ~\$1 B U.S. commercial investment in GPS receiver equipment and technology development, and NASA and NSF's multi-\$M R&D investment in GPS applications and technology development through GST and UNAVCO.

TRANSITIONS

We are still in the demonstration phase. With the significant results obtained so far, we are planning to move forward with the demonstration of a prototype system. In addition, industry has recently developed advanced GPS tracking receivers and antennas with improved phase tracking performance at low elevation angles. Our results and the industry developments should enable transition to use in the Navy fleet after our demonstration is completed.

RELATED PROJECTS

Kenn Anderson is developing techniques that use amplitude measurements for the detection of specific refractivity profiles. Dr. Anderson's amplitude approach and the phase approach under development by may best work together. The Department of Energy has funded UCAR to develop low-cost L1-only GPS systems for tropospheric tomography. This study requires the measurement of single transmitter - receiver slant ranges. NCAR scientists are beginning work to assimilate single GPS slant measurements into numerical weather models. The slant measurement techniques that we are developing with this study can then be applied to numerical weather forecasting.

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RELEVANT WEB ADDRESSES

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